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## Observation of $B^+ \rightarrow p\bar{\Lambda}\gamma$

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## Abstract

We report the first observation of the radiative hyperonic  $B$  decay  $B^+ \rightarrow p\bar{\Lambda}\gamma$ , using a  $140\text{ fb}^{-1}$  data sample recorded on the  $\Upsilon(4S)$  resonance with the Belle detector at the KEKB asymmetric energy  $e^+e^-$  collider. The measured branching fraction is  $\mathcal{B}(B^+ \rightarrow p\bar{\Lambda}\gamma) = (2.16_{-0.53}^{+0.58} \pm 0.20) \times 10^{-6}$ . We examine its  $M_{p\bar{\Lambda}}$  distribution and observe a peak near threshold. This feature is expected by the short-distance  $b \rightarrow s\gamma$  transition. A search for  $B^+ \rightarrow p\bar{\Sigma}^0\gamma$  yields no significant signal and we set a 90% confidence-level upper limit on the branching fraction of  $\mathcal{B}(B^+ \rightarrow p\bar{\Sigma}^0\gamma) < 4.6 \times 10^{-6}$ .

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The  $b \rightarrow s\gamma$  penguin diagram is responsible for the large rates of the observed radiative  $B \rightarrow K^*\gamma$  [1] decays. It is also a good probe of new physics beyond the Standard Model [2]. Recently, the Belle collaboration reported a very stringent limit of  $\mathcal{O}(10^{-6})$  on the branching fraction of two-body  $B^+ \rightarrow p\bar{\Lambda}$  decays [3] but found an unexpectedly large rate for the three-body decay  $B^0 \rightarrow p\bar{\Lambda}\pi^-$  [4], which proceeds, presumably, via the  $b \rightarrow s$  penguin process. One interesting feature of the  $B^0 \rightarrow p\bar{\Lambda}\pi^-$  decay is that the observed proton- $\bar{\Lambda}$  mass  $M_{p\bar{\Lambda}}$  spectrum peaks near threshold. Naively, a suppression of  $\mathcal{O}(\alpha_{EM})$  is expected for the  $B^+ \rightarrow p\bar{\Lambda}\gamma$  decay relative to  $B^+ \rightarrow p\bar{\Lambda}$  if the former process is bremsstrahlung-like. In contrast, a short-distance  $b \rightarrow s\gamma$  contribution can lead naturally to a non-bremsstrahlung-like energetic photon spectrum and an enhancement of  $M_{p\bar{\Lambda}}$  at low mass; the former distribution can be compared to the recently measured  $b \rightarrow s\gamma$  inclusive photon energy spectrum [5]. These features motivate our study of  $B^+ \rightarrow p\bar{\Lambda}\gamma$ . Some theoretical predictions [6] for the branching fraction of  $B^+ \rightarrow p\bar{\Lambda}\gamma$  are at the  $10^{-6}$  level, which is in the sensitivity range of the B-factories.

We use a data sample of  $152 \times 10^6$   $B\bar{B}$  pairs, corresponding to an integrated luminosity of  $140 \text{ fb}^{-1}$ , collected by the Belle detector at the KEKB [7] asymmetric energy  $e^+e^-$  collider. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect  $K_L^0$  mesons and to identify muons. The detector is described in detail elsewhere [8].

To identify the charged tracks, the proton ( $L_p$ ), pion ( $L_\pi$ ) and kaon ( $L_K$ ) likelihoods are determined from the information obtained by the hadron identification system (CDC, ACC and TOF). Prompt proton candidates must satisfy the requirements of  $L_p/(L_p + L_K) > 0.6$  and  $L_p/(L_p + L_\pi) > 0.6$ , and not be associated with the decay of a  $\Lambda$  baryon. The proton selection efficiency is about 84% (88% for  $p$  and 80% for  $\bar{p}$ ) for particles with momenta at 2 GeV/ $c$ , and the fake rate is about 10% for kaons and 3% for pions.

The prompt proton candidates are also required to satisfy track quality criteria based on track impact parameters relative to the interaction point (IP). The deviations from the IP position are required to be within 0.3 cm in the transverse ( $x$ - $y$ ) plane, and within  $\pm 3$  cm in the  $z$  direction, where the  $z$  axis is opposite the direction of the positron beam. Candidate

$\Lambda$  baryons are reconstructed from two oppositely charged tracks, one treated as a proton and the other as a pion, and must have a mass within  $5\sigma$  of the nominal  $\Lambda$  mass, as well as a displaced vertex and flight direction consistent with a  $\Lambda$  originating from the interaction point. To reduce background, a  $L_p/(L_p + L_\pi) > 0.6$  requirement is applied to the proton-like track. Photon candidates are selected from the neutral clusters within the barrel ECL (with polar angle between  $33^\circ$  and  $128^\circ$ ) having energy greater than 500 MeV. We discard any photon candidate if the mass, in combination with any other photon above 30 (200) MeV, is within  $\pm 18$  ( $\pm 32$ )  $\text{MeV}/c^2$  of the nominal mass of the  $\pi^0$  ( $\eta$ ) meson. The above selection criteria are optimized using Monte Carlo (MC) simulated event samples.

Candidate  $B$  mesons are formed by combining a proton with a  $\bar{\Lambda}$  and a photon [9], each defined using the above criteria, and requiring the beam-energy constrained mass,  $M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2}$ , and the energy difference,  $\Delta E = E_B - E_{\text{beam}}$ , to lie in the ranges  $5.2 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$  and  $-0.2 \text{ GeV} < \Delta E < 0.5 \text{ GeV}$ . Here,  $p_B$  and  $E_B$  refer to the momentum and energy, respectively, of the reconstructed  $B$  meson, and  $E_{\text{beam}}$  refers to the beam energy, all in the  $\Upsilon(4S)$  rest frame. Because of the  $\Delta E > -0.2 \text{ GeV}$  requirement, background from  $B$  feed-down is negligible except that from  $B^+ \rightarrow p\bar{\Sigma}^0\gamma$  decay where  $\bar{\Sigma}$  subsequently decays to  $\bar{\Lambda}\gamma$  almost 100% of the time. The  $p\bar{\Sigma}^0\gamma$  events can form a nearby peak (shifted about -100 MeV in  $\Delta E$ ) with respect to the signal peak in the  $M_{bc} - \Delta E$  region.

The dominant background for  $B^+ \rightarrow p\bar{\Lambda}\gamma$  decay is from continuum  $e^+e^- \rightarrow q\bar{q}$  processes, where  $q = u, d, s, c$ . The continuum background is evaluated with an MC sample of 120 million continuum events. In the  $\Upsilon(4S)$  rest frame, continuum events are jet-like while  $B\bar{B}$  events are spherical. We follow the scheme defined in Ref. [10] and combine seven shape variables to form a Fisher discriminant [11] in order to maximize the distinction between continuum processes and signal. The variables used have almost no correlation with  $M_{bc}$  and  $\Delta E$ . Probability density functions (PDFs) for the Fisher discriminant and the cosine of the angle between the  $B$  flight direction and the beam direction in the  $\Upsilon(4S)$  frame are combined to form the signal (background) likelihood  $\mathcal{L}_s$  ( $\mathcal{L}_b$ ). We require the likelihood ratio  $\mathcal{R} = \mathcal{L}_s/(\mathcal{L}_s + \mathcal{L}_b)$  to be greater than 0.75; this suppresses about 86% of the background while retaining 78% of the signal. The optimal selection requirement is determined by maximizing  $N_s/\sqrt{N_s + N_b}$ , where  $N_s$  and  $N_b$  denote the expected number of signal and background events; here a signal branching fraction of  $4 \times 10^{-6}$  is assumed.

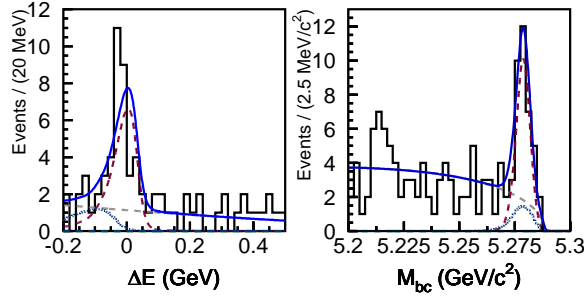


FIG. 1: The distributions of  $\Delta E$  (for  $M_{bc} > 5.27 \text{ GeV}/c^2$ ) and  $M_{bc}$  (for  $-0.135 \text{ GeV} < \Delta E < 0.074 \text{ GeV}$ ) for  $B^0 \rightarrow p\bar{\Lambda}\gamma$  candidates having  $M_{p\bar{\Lambda}} < 2.4 \text{ GeV}/c^2$ . The solid, light dashed and dark dashed lines represent the combined fit result, fitted background and fitted signal, respectively. The dotted lines represent projections of 10 assumed  $p\bar{\Sigma}^0\gamma$  events for comparison.

We perform an unbinned extended maximum likelihood fit to the events with  $-0.2 \text{ GeV} < \Delta E < 0.5 \text{ GeV}$  and  $M_{bc} > 5.2 \text{ GeV}/c^2$  in order to determine the signal yield,  $\Sigma$  feed-down, and  $q\bar{q}$  background. The extended likelihood function is defined as

$$\mathcal{L} = \frac{e^{-(N_\Lambda + N_\Sigma + N_{q\bar{q}})}}{N!} \prod_{i=1}^N \left[ N_\Lambda P_\Lambda(M_{bc_i}, \Delta E_i) + N_\Sigma P_\Sigma(M_{bc_i}, \Delta E_i) + N_{q\bar{q}} P_{q\bar{q}}(M_{bc_i}, \Delta E_i) \right],$$

where  $N$  is the total number of events in the fit;  $P_\Lambda$ ,  $P_\Sigma$ , and  $P_{q\bar{q}}$  are the PDFs for  $p\bar{\Lambda}\gamma$ ,  $p\bar{\Sigma}^0\gamma$ , and continuum background, respectively;  $N_\Lambda$ ,  $N_\Sigma$ , and  $N_{q\bar{q}}$  are the corresponding number of candidates.

The  $p\bar{\Lambda}\gamma$  and  $p\bar{\Sigma}^0\gamma$  PDFs are two-dimensional functions approximated by smooth histograms from MC simulation. We use the parametrization first suggested by the ARGUS collaboration [12],  $f(M_{bc}) \propto M_{bc} \sqrt{1 - (M_{bc}/E_{\text{beam}})^2} \exp[-\xi(1 - (M_{bc}/E_{\text{beam}})^2)]$ , to model the background  $M_{bc}$  distribution, and a quadratic polynomial for the background  $\Delta E$  shape. We perform a two-dimensional unbinned fit to the  $\Delta E$  vs  $M_{bc}$  distribution, with the signal and background normalizations as well as the continuum background shape parameters allowed to float.

The  $\Delta E$  distribution (with  $M_{bc} > 5.27 \text{ GeV}/c^2$ ) and the  $M_{bc}$  distribution (with  $-0.135 \text{ GeV} < \Delta E < 0.074 \text{ GeV}$ ) for the region  $M_{p\bar{\Lambda}} < 2.4 \text{ GeV}/c^2$  are shown in Fig. 1 along with the projections of the fit. The two-dimensional unbinned fit gives a  $B^+ \rightarrow p\bar{\Lambda}\gamma$  signal yield of  $34.1^{+7.1}_{-6.6}$  with a statistical significance of 8.6 standard deviations and a  $B^+ \rightarrow p\bar{\Sigma}^0\gamma$  yield

of  $0.0 \pm 4.7$ . The significance is defined as  $\sqrt{-2\ln(L_0/L_{\max})}$ , where  $L_0$  and  $L_{\max}$  are the likelihood values returned by the fit with signal yield fixed at zero and its best fit value, respectively.

We measure the differential branching fraction of  $p\bar{\Lambda}\gamma$  by fitting the yield in bins of  $M_{p\bar{\Lambda}}$ , as shown in Fig. 2, and correcting for the corresponding detection efficiency as determined from a large MC sample of events distributed uniformly in phase space. The results of the fits along with the efficiencies and the partial branching fractions are given in Table I. In these fits, the signal yields are constrained to be non-negative. The yield is consistent with null signal for higher  $M_{p\bar{\Lambda}}$  bins if the non-negative constraint is removed. The observed mass distribution in Fig. 2 peaks at low  $p\bar{\Lambda}$  mass, a feature seen also in  $B^0 \rightarrow p\bar{\Lambda}\pi^-$  and  $B^+ \rightarrow p\bar{p}K^+$  decays [4, 13].

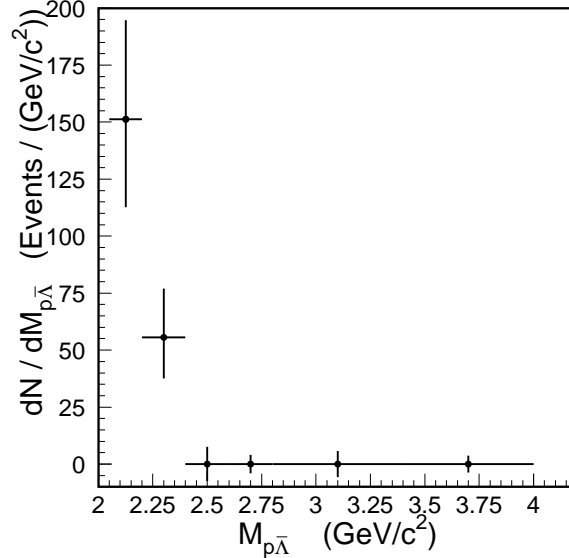


FIG. 2: The differential yield for  $B^0 \rightarrow p\bar{\Lambda}\gamma$  as a function of  $M_{p\bar{\Lambda}}$ .

We also study the angular distribution of the proton in the baryon pair system. The angle  $\theta_X$  is measured between the proton direction and the  $\gamma$  direction in the baryon pair rest frame. Figure 3 shows the efficiency corrected  $B$  yield in bins of  $\cos\theta_X$ . This distribution supports the  $b \rightarrow s\gamma$  fragmentation picture where the  $\Lambda$  tends to emerge opposite the direction of the photon. We define the angular asymmetry as  $A = \frac{N_{\cos\theta_{X+}} - N_{\cos\theta_{X-}}}{N_{\cos\theta_{X+}} + N_{\cos\theta_{X-}}}$ , where  $N_{\cos\theta_{X+}}$  and  $N_{\cos\theta_{X-}}$  stand for the efficiency corrected  $B$  yield with  $\cos\theta_X > 0$  and  $\cos\theta_X <$

TABLE I: The event yield, efficiency, and branching fraction ( $\mathcal{B}$ ) for each  $M_{p\bar{\Lambda}}$  bin.

$M_{p\bar{\Lambda}}$ (GeV/ $c^2$ )	Signal Yield	Efficiency(%)	$\mathcal{B}$ ( $10^{-6}$ )
$< 2.2$	$22.7^{+6.5}_{-5.8}$	10.6	$1.41^{+0.40}_{-0.36}$
$2.2 - 2.4$	$11.1^{+4.3}_{-3.6}$	9.8	$0.74^{+0.29}_{-0.24}$
$2.4 - 2.6$	$0.0^{+1.5}_{-1.5}$	9.3	$0.00^{+0.11}_{-0.11}$
$2.6 - 2.8$	$0.0^{+0.8}_{-0.8}$	9.9	$0.00^{+0.06}_{-0.06}$
$2.8 - 3.4$	$0.0^{+3.4}_{-3.4}$	9.6	$0.00^{+0.23}_{-0.23}$
$3.4 - 4.0$	$0.0^{+2.2}_{-2.2}$	9.6	$0.00^{+0.15}_{-0.15}$
Total	$33.8^{+9.0}_{-8.1}$	-	$2.16^{+0.58}_{-0.53}$

0, respectively. The measured value for  $A$  is  $0.36^{+0.23}_{-0.20}$ .

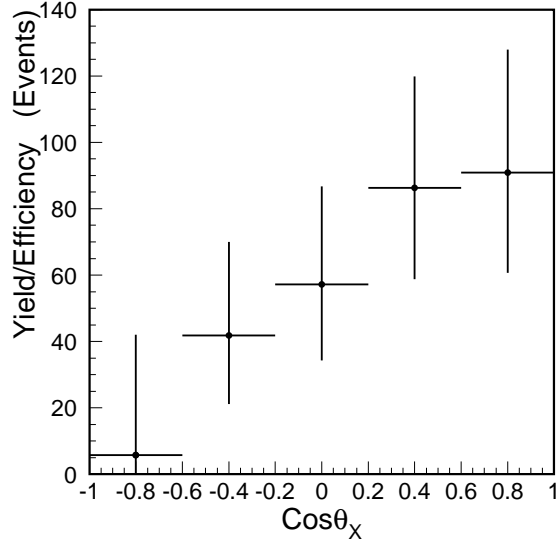


FIG. 3: Efficiency corrected yield versus  $\cos \theta_X$  in the baryon pair system.

The systematic uncertainty in particle selection is studied using high statistics control samples. Proton identification is studied with a  $\Lambda \rightarrow p\pi^-$  sample. The tracking efficiency is studied with a  $D^*$  sample, using both full and partial reconstruction. Based on these studies, we sum the correlated errors linearly and assign a 4.1% error for proton identification and 4.9% for the tracking efficiency.



For  $\Lambda$  reconstruction, we have an additional uncertainty of 2.5% on the efficiency for off-IP track reconstruction, determined from the difference of  $\Lambda$  proper time distributions for data and MC simulation. There is also a 1.2% error associated with the  $\Lambda$  mass selection and a 0.5% error for the  $\Lambda$  vertex selection [3]. Summing the errors for  $\Lambda$  reconstruction, we obtain a systematic error of 2.8%.

The 2.2% uncertainty for the photon detection is determined from radiative Bhabha events. For the  $\pi^0$  and  $\eta$  vetoes, we compare the fit results with and without the vetoes; the difference in the branching fraction is 0.5%, which is taken as the associated systematic error.

Continuum suppression is studied by varying the selection criteria on  $\mathcal{R}$  in the interval  $0 - 0.9$  to see if there is any systematic trend in the signal fit yield. We quote a 2.5% error for this.

The systematic uncertainty from fitting is 2.2%, which is determined by assuming uncorrelated  $M_{bc}$  and  $\Delta E$  PDFs, and by varying the parameters of the signal and background PDFs by  $\pm 1\sigma$ . The MC statistical uncertainty and modeling with six  $M_{p\bar{\Lambda}}$  bins contributes a 4.4% error (obtained by changing the  $M_{p\bar{\Lambda}}$  bin size). The error on the number of total  $B\bar{B}$  pairs is 0.5%. The error from the sub-decay branching fraction of  $\Lambda \rightarrow p\pi^-$  is 0.8% [14].

We combine the above uncorrelated errors in quadrature. The total systematic error is 9.2%.

We see no evidence for the decay  $B^+ \rightarrow p\bar{\Sigma}^0\gamma$ . We use the fit results to estimate the expected background, and compare this with the observed number of events in the  $p\bar{\Sigma}^0\gamma$  signal region ( $-0.20 \text{ GeV} < \Delta E < 0.04 \text{ GeV}$  and  $M_{bc} > 5.27 \text{ GeV}/c^2$ ) in order to set an upper limit on the yield [15, 16, 17]. The estimated background for  $M_{p\bar{\Lambda}} < 4.0 \text{ GeV}/c^2$  is  $84.0 \pm 9.2$ , the number of observed events is 96, and the systematic uncertainty is 9.2%; from these, the upper limit yield is 35.5 at 90% confidence level. Assuming the  $B^0 \rightarrow p\bar{\Sigma}^0\gamma$  three-body decay is uniform in phase space, the overall efficiency including the loss from the  $M_{p\bar{\Lambda}} < 4.0 \text{ GeV}/c^2$  requirement is 5.1%; the 90% confidence-level upper limit for the branching fraction is  $\mathcal{B}(B^0 \rightarrow p\bar{\Sigma}^0\gamma) < 4.6 \times 10^{-6}$ .

In summary, we have performed a search for the radiative baryonic decays  $B^+ \rightarrow p\bar{\Lambda}\gamma$ , and  $p\bar{\Sigma}^0\gamma$  with 152 million  $B\bar{B}$  events. A clear signal is seen in the  $p\bar{\Lambda}\gamma$  mode, and we measure a branching fraction of  $\mathcal{B}(B^+ \rightarrow p\bar{\Lambda}\gamma) = (2.16_{-0.53}^{+0.58} \text{ (stat)} \pm 0.20 \text{ (syst)}) \times 10^{-6}$ , which is consistent with the upper limit set by CLEO[18]. The yield of the  $B^0 \rightarrow p\bar{\Sigma}^0\gamma$

mode is not statistically significant, and we set the 90% confidence level upper limit of  $\mathcal{B}(B^0 \rightarrow p\bar{\Sigma}^0\gamma) < 4.6 \times 10^{-6}$ .

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